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THE INNER JET OF THE RADIO GALAXY M87

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ABSTRACT

We report new 2 cm VLBA images of the inner radio jet of M87 showing a limb brightened structure and unambiguous evidence for a faint 3 mas long counter-feature which also appears limb brightened. Multi-epoch observations of seven separate jet features show typical speeds of less than a few percent of the speed of light, despite the highly asymmetric jet structure and the implications of the canonical relativistic beaming scenario. The observed morphology is consistent with a two stream spine-sheath velocity gradient across the jet, as might be expected from the recently discovered strong and variable TeV emission as well as from numerical modeling of relativistic jets. Considering the large jet to counter-jet flux density ratio and lack of observed fast motion in the jet, we conclude that either the inner part of the M87 jet is intrinsically asymmetric or that the bulk plasma flow speed is much greater than any propagation of shocks or other pattern motions.

Subject headings: galaxies: active — galaxies: jets — galaxies: individual (M87) — radio continuum: galaxies — acceleration of particles

1. INTRODUCTION

The peculiar galaxy M87 in the Virgo cluster was among the first to be recognized as a powerful source of radio emission. More than 40 years ago, Shklovsky (1964) argued that since radio galaxies such as Cygnus A typically have symmetric lobes, the jets which feed the radio lobes are likely to be intrinsically two-sided, but that they would appear one-sided due to differential relativistic Doppler beaming. This simple picture is now widely accepted as the basis of unified models, which try to explain many of the different properties of AGN as due to relativistic beaming and projection effects, rather than to intrinsic differences (e.g., Urry & Padovani 1995).

M87 remains of great interest today, since there is strong observational evidence for a $3\times10^9\ M_\odot$ black hole located at the galactic nucleus thought to power the relativistic jet (Harms et al. 1994; Macchetto et al. 1997). Moreover, at a distance of only 16 Mpc, (1 mas = 0.08 pc; 1 mas per year = 0.25c) M87 is one of the closest radio galaxies, and as such it has one of the few jets which can be well-resolved on sub-parsec scales in a direction transverse to the flow.

The M87 jet has been studied over a wide range of the electromagnetic spectrum, including imaging with HST (Biretta et al. 1999) and the VLA (Owen et al. 1989) as well as with Chandra (Wilson & Yang 2002; Harris et al. 2006). The observed morphology at radio, optical, and even X-ray wavelengths appears very similar, suggesting a common synchrotron radiation mechanism at all wavelengths and a common spectral index of –0.67 throughout the jet (Perlman et al. 2001). At least at optical and X-ray wavelengths, the electron lifetime down the jet is much shorter than the travel time from the nucleus, suggesting continual in situ acceleration of relativistic particles within the jet (Perlman et al. 2001).

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In this paper we report on observations made with the NRAO Very Long Baseline Array (VLBA) at 2 cm wavelength. High dynamic range images constructed from observations made in the year 2000 describe the two-dimensional structure of the jet out to nearly 0.2 arcsec (16 pc) and show the presence of a faint counter-feature. These observations were complemented by regular observations made with lower sensitivity between 1995 and 2007 to study the outward flow within the inner part of the radio jet.

2. THE OBSERVATIONS AND IMAGING

M87 has been regularly observed with the VLBA since 1995 as part of the 2 cm VLBA survey (Kellermann et al. 1998) and the more recent MOJAVE program (Lister & Homan 2005). In these programs, at each epoch we observed each source for a total of about one hour, with multiple observations spaced over a wide range of hour angle. For M87, we have obtained a total of 21 images between 1995 and 2007. Typically the rms noise in each image is about 0.3 mJy beam^{-1}. As described in more detail by Kellermann et al. (1998, 2004) and Lister & Homan (2005), for each epoch, the data were calibrated using AIPS and imaged with Difmap. The location of each bright feature was fitted in the visibility plane.

We have supplemented these multiple epoch images using VLBA 2 cm archive data from observations made at three epochs in 2000 (22 January, 8 May, 30 December). These later observations included one VLA antenna and were made with full tracks in hour angle each lasting about 10 hours using 2-bit recording at a 256 Mbps data rate, allowing us to reach the thermal noise level of less than 70 μJy beam^{-1}.

As a check on the robustness of the weak features seen in these high dynamic range images, different authors independently made images using Difmap and AIPS respectively and obtained very similar results. In addition, to verify the reality of faint "counter-feature" reported in §3, one of us generated three artificial datasets of M87. These model datasets were based on the structure of M87 which was observed on 2000 May 8. They used the identical (u,v)-coverage of that epoch and contained a comparable level of random noise. One of the models contained an extended counter-feature totaling nearly 40 mJy, and two did not. All three model datasets

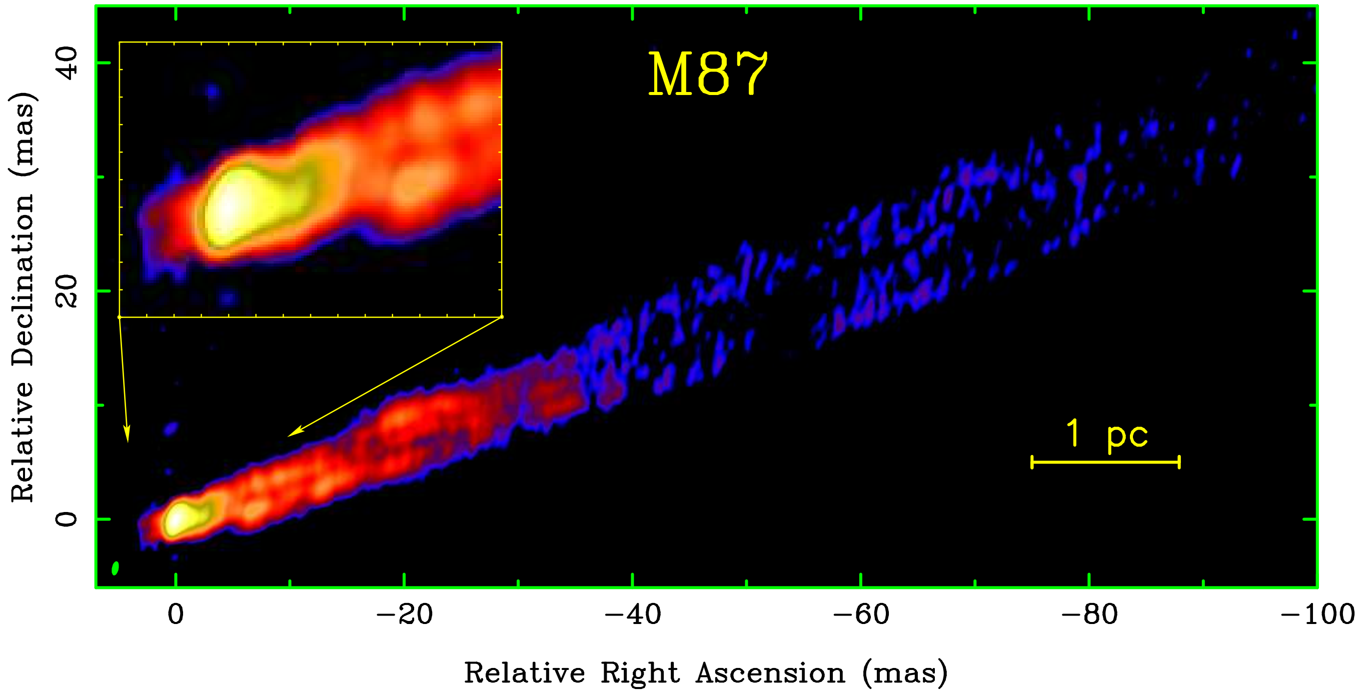

FIG. 1.— VLBA 2 cm logarithmic false-color image of the M87 jet. The beam, FWHM of 0.6 by 1.3 mas at P.A. = −11° is shown in the lower left hand corner. The peak intensity is 1.00 Jy beam^{-1} and the off-source rms noise 64 μJy beam^{-1}. The corresponding dynamic range is better than 15,000 to 1. This image was obtained from a full track in hour angle using the VLBA along with one VLA antenna on 2000 May 8. The faint counter-jet is seen extending to the southeast.

were independently self-calibrated and imaged by another one of us without any prior communication about which models contained the counter-feature. The image maker was able to correctly identify the data with the counter-feature and correctly determined its flux density and extended structure. No counter-feature was found in the derived image down to the noise level from the other two datasets without the counter-feature. Given the results of these trials, and the presence of the counter-feature in all three observed full-track VLBA images as well as in the 20 lower sensetivity 2 cm Survey / MOJAVE images , we are confident that the observed counter-feature is real and that there are no significant artifacts in our image created by the imaging process.

3. JET STRUCTURE

In Figure 1, we show the 2 cm image constructed from observations made with the VLBA plus 1 VLA antenna. A tapered image made with twice the beam size from the same data shows structure out to nearly 0.2 arcsec. As seen in Figure 1, the jet appears bifurcated, starting at about 5 mas (0.4 pc) from the core, characteristic of a single limb brightened cylindrical or conical jet. The M87 jet appears to be highly collimated, with re-collimation observed between 2 pc where the opening angle is about 16°, and 12 pc where the opening angle is only 6° to 7°. As discussed in §2, Figure 1 also shows the existence of weak structure extending away from the bright core toward the southeast. Indications of this counter feature were first suggested by Ly et al. (2004) on the basis of their 7 mm VLBA observations. This counter-feature also appears clearly bifurcated but is weaker than the main jet by a factor of 10 to 15 close to the core and is only traced out to 3.1 mas from the core. Between 3.1 and 6 mas away, this feature is weaker than the jet by at least a factor of 200.

For several reasons we believe that the eastern extension may be the counter-jet. Based on their higher resolution 7 mm image, Ly et al. (2007) have also detected the counter feature and have argued that the true base of the jet cannot be offset by more than 2 mas from the bright core; whereas we have detected the counter-feature to be at least 3.1 mas long. Also, we note strong circular polarization at a fractional level of $-0.5\% \pm 0.1\%$ was detected at 2 cm by Homan & Lister (2006) coincident with the flux density peak, suggesting that this region of the jet has an optical depth near unity (e.g., Jones 1988) which is characteristic of jet cores. Keeping in mind that there is possible ambiguity in the VLBI image alignment, Zavala & Taylor (2003) have measured the spectral index between 8 GHz and 12 GHz for the region with the peak intensity to be $\alpha = 0.24$ ($S \sim \nu^{\alpha}$) consistent with an optically thick nucleus. Since the surface brightness of the eastern feature is more than 200 times fainter than the one of the brightest feature which we have identified with the core, it seems unlikely that it could be the actual core. However, considering that no other radio jet has been observed with comparable linear resolution, sensitivity, and dynamic range, we cannot exclude the possibility that we are seeing the detailed structure of the optically thick core of the jet, and that the counter-jet itself is not detected.

4. JET KINEMATICS

HST observations of the M87 jet made between 1994 and 1998 by Biretta et al. (1999) have suggested superluminal speeds up to about 6c in a region approximately 6 arcsec (0.5 kpc) downstream of the central AGN, consistent with what might be expected from Doppler boosting of this highly asymmetric jet. The feature, known as HST-1, is located 0.86 arcsec from the base of the jet, and was more recently observed by Chandra and HST to vary dramatically at both X-ray and optical wavelengths (Harris et al. 2003, 2006; Cheung et al. 2007). It was found to have apparent superluminal speeds up to $4.3 \pm 0.7c$ in 20 cm VLBA experiment

TABLE 1
M87 JET COMPONENTS SPEED

Component (1)	$<R>$ (mas) (2)	σ_R (mas) (3)	$<\vartheta>$ (deg) (4)	μ_r (μas yr^{-1}) (5)	β_{app} (6)
C7	0.43	0.1	111.2	40 ± 6	0.010 ± 0.001
C6	0.43	0.1	279.2	13 ± 6	0.003 ± 0.001
C5	1.4	0.2	283.8	59 ± 11	0.015 ± 0.003
C4	2.8	0.3	283.5	104 ± 17	0.026 ± 0.004
C3	6.4	0.5	282.8	82 ± 26	0.021 ± 0.007
C2	13	1.3	286.6	216 ± 81	0.05 ± 0.02
C1	21	1.1	290.0	12 ± 76	0.00 ± 0.02

NOTE. — Col. (1): Component identifier, Col. (2): Mean radial position relative to the core, Col. (3): Typical radial position error calculated from the scatter of points from the linear fit (Figure 2), Col. (4): Mean position angle relative to the core, Col. (5): Angular radial speed and 1σ uncertainty. Positive speed means that a component is receding from the core, negative—approaching the core, Col. (6): Radial speed in units of the speed of light and 1σ uncertainty.

by Cheung et al. (2007). However, within 1 arcsec of the nucleus (80 pc), using HST, Biretta et al. (1999) measured much slower speeds between 0.6c and 0.8c.

At radio wavelengths, Biretta et al. (1995) reported VLA observations which showed a typical speed of about 0.5c but ranging up to 2.5c at distances up to about 20 arcsec (1.6 kpc) from the nucleus. However, previous VLBA observations (Biretta & Junor 1995; Junor & Biretta 1995) and VSOP (VLBA to HALCA) observations (Dodson et al. 2006) found no evidence of motions within 5 pc of the core, although Reid et al. (1989) reported an observed velocity of $0.28c \pm 0.08c$ for a feature located about 20 mas (1.6 pc) from the nucleus. More recently, based on just two of five total epochs, Ly et al. (2007) reported possible speeds between 0.25c and 0.4c for three transient features located about 3 mas (0.24 pc) from the nucleus.

We find no evidence for motions faster than 0.07c within the inner 20 mas (1.6 pc). In Figure 2 we plot the location of seven separate jet features as a function of time, and we summarize their speeds in Table 1. All the jet components were fit with circular Gaussians. The fastest jet speed observed is

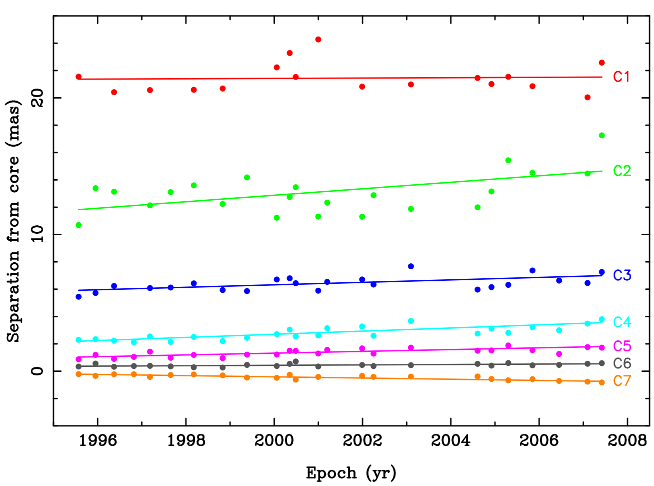

FIG. 2.— The location of seven separate features which were seen at multiple epochs are plotted as a function of time. Component C7 refers to the counter-jet. Typical errors of the components' separation are presented in Table 1. The large scatter in the positions of the outer two components, C1 and C2, is due primarily to their large angular extent which makes location of their centroids uncertain in our snap-shot images of the limb-brightened jet.

only $0.026 \pm 0.004c$, while the counter-jet feature apparently moves outward at $0.010 \pm 0.001c$. The other five features appear essentially stationary over the twelve years that they have been observed, with nominal upper limits to their speed of about 0.07c. Each feature was detected at 17 to 24 separate epochs.

Given that much faster speeds, up to 6c, have been observed in the arcsecond scale jet, it is important to consider the possibility of temporal under-sampling in our kinematic analysis of the milli-arcsecond scale jet, where 6c would correspond to $\simeq 24$ mas yr^{-1}. Our VLBA sampling interval ranged from 2 to 8 months, with a median of 5 months. A newly ejected, fast component could therefore conceivably travel anywhere between 2 to 16 mas downstream in the time between successive epochs, possibly leading to an incorrect component cross-identification in Figure 2. However, the large number of jet components present at each epoch implies that if they have very fast speeds, new components would have to be emitted very frequently from the core region, at a rate of ~ 2 per year. But, the flux density and brightness temperature of the core show no indication of such activity, but instead vary relatively smoothly over time. Second, there are clear gaps in jet brightness between 3 and 5 mas and between 6 and 10 mas (see Figure 2 and the movie in the electronic edition of the Journal) in which jet components are never present at any epoch — a highly unlikely situation given a high component ejection rate. Third, the brightness temperatures of the individual components C1 to C7 are consistent across the epochs, which would not be expected if our cross-identifications were incorrect. Finally, our 2 cm VLBA movie of the jet[6], which relies on simple linear interpolation across the epochs, shows no sudden jumps that would be indicative of temporal undersampling.

We believe that this interpretation is more robust than the results of other radio measurements which typically used only two or three epochs. We cannot rule out the possibility of a smooth relativistic flow with no propagating shocks or other patterns.

5. DISCUSSION

Considering that the Doppler boosted relativistic jet of M87 appears one-sided out to kiloparsec scales, the absence of any clear motions in the inner jet is somewhat surprising. We measure a jet to counter-jet flux density ratio of between 10 and 15 (in the year 2000) at a position between 0.5 and 3.1 mas from the core, and a lower limit of 200 between 3.1 to 6.0 mas away. Assuming that the jet is intrinsically bidirectional and symmetric, and that the bulk velocity flow is the same as the pattern motion, our maximum reliable observed speed of $\beta_{app} = 0.026 \pm 0.004$ would imply a jet to counter-jet ratio near unity for the commonly accepted viewing angle of $\sim 40°$ (e.g. Owen et al. 1989; Reid et al. 1989). If the jet and counter-jet are intrinsically symmetric and oriented at an angle of 30° to 40° to the line of sight, the observed jet to counter-jet flux density ratios imply that the intrinsic flow speed, β, is 0.5 to 0.6 between 0 and 3.1 mas from the core and increases to >0.9 beyond 3.1 mas. Also, we note that the rather small ratio of observed jet to counter-jet speeds (Ta-

[6] A movie of the jet covering the period 1999 to 2007 can be seen in electronic edition of the Astrophysical Journal. The maps prior to 1999 have a higher noise, they were not included in the movie. An up to date version of the movie, as well as a journal of the observations, image and visibility FITS files can be found in our web database http://www.physics.purdue.edu/MOJAVE/sourcepages/1228+126.shtml

ble 1) of less than 2.5 is not consistent with simple relativistic beaming models. We conclude that either the inner jet is intrinsically asymmetric, or there are no detectable moving features within a rapidly flowing plasma.

Apparent limb brightening is predicted from analytic and numerical modeling of relativistic jets (Aloy et al. 2000; Perucho et al. 2007) and can be reproduced via Kelvin-Helmholtz instability, which is seen in extragalactic jets both at kiloparsec (M87, Lobanov et al. 2003) and parsec scales (3C273, Lobanov & Zensus 2001). Limb brightening can be particularly pronounced when the jet opening angle is greater than the beaming angle (Gopal-Krishna et al. 2006) and especially if there is a velocity gradient across the jet (Gopal-Krishna et al. 2007). A two layer "spine-sheath" model has been suggested to explain the existence of observed strong TeV emission from BL Lacs with apparently slow moving radio jets (Chiaberge et al. 2000; Piner & Edwards 2004; Giroletti et al. 2004). Stawarz & Ostrowski (2002) and Ghisellini et al. (2005) have considered a two component jet having a fast spine which produces the gamma ray emission by inverse Compton scattering of the radio photons from a surrounding slow layer or sheath. Spine-sheath models have also been discussed by Bridle (1996), Swain et al. (1998), Attridge et al. (1999), Laing & Bridle (2002), and Cohen et al. (2007). The central gap seen in our VLBA images of M87, as well as observed TeV emission (Aharonian et al. 2006, and as discussed above) combined with the lack of measurable motion within the inner 1.6 pc (§4) appear to support this two component model.

The recently reported detection of strong variable TeV emission from M87 (Aharonian et al. 2006) also presents a problem, since unless the radiating plasma has a large Doppler factor, energy losses due to $\gamma-\gamma$ pair production will extinguish the gamma ray emission (e.g., Dondi & Ghisellini 1995). Although we do not find any evidence for a fast moving jet in M87 close to the central engine, the observed TeV emission can be explained in terms of a dual layer model with a fast inner jet and a slower moving outer layer (Ghisellini et al. 2005). In this picture, the inner jet is beamed away from us and is thus not seen in our VLBA images, and we only observe the slower outer layer. However, even the slow outer layer must move at at least $\beta > 0.5$–0.8 to be consistent with the jet to counter-jet flux density ratio as discussed earlier in this section.

Cheung et al. (2007) argue that the superluminal feature HST-1, located at a de-projected distance of more than 100 pc down the jet, may be the source of TeV emission in M87, rather than the base of the jet. By analogy, they suggest that blazar activity more broadly may not, as is widely assumed, be located close to the central engine. If this is the case, we might expect to observe small-scale structure in HST-1 at 2 cm, but we do not find any milliarcsecond structure stronger than 0.75 mJy in that region in the 2000 full-track VLBA data; however our data were taken five years before the HST-1 flaring event in 2005. Aharonian et al. (2006) commented that an origin of the TeV emission in HST-1 would imply an unrealistically small opening angle for the energy source, assuming the source was located at the base of the jet.

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Facilities: VLBA, VLA.

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